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SUMMARY

A flight investigation has been conducted to determine the steep instrument approach capabilities and limitations of a C-47 airplane under manual control. This study included an investigation of flare paths suitable for transition from the steep glide slope to a final terminal angle to touchdown.

The maximum glide slope feasible for operational use in an instrument approach was 6°. More pilot effort and concentration were required to fly the 6° glide slope than were required for the $2\frac{1}{2}^{\circ}$ slope and the flight-path deviations were also somewhat greater for the 6° slope.

The greatest problem during the approach or flare was the effort required to maintain the proper lateral directional control. In the opinion of most of the pilots, instrument approaches to touchdown could be made repeatedly with manual longitudinal control if lateral directional control was automatic.

The most suitable flare paths were those which required 4 to 6 seconds per degree of flight-path change from the 6° glide slope to the final terminal angle.

INTRODUCTION

In making the normal instrument approach $\left(2\frac{1}{2}^{\circ}\text{ to }3^{\circ}\text{ glide slope}\right)$, the current turbojet transports use a large amount of airspace. In addition, the engines of these transports produce noise of an objectionable level when the long low instrument approach takes the turbojets over populated areas. According to reference 1, the most frequent public complaints today are concerned with the approach noise rather than the take-off noise. In regard to the landing-approach engine noise, some recent studies have indicated that the supersonic transport is expected to be even more severe than the current turbojets. One method of reducing both the airspace requirements and the ground noise level would be to steepen the approach glide slope. An investigation was, therefore, undertaken on several different types of airplanes to determine

the steep approach capabilities of these airplanes and how the steep approach capabilities are influenced by airplane characteristics. This report covers studies on a C-47 airplane which is a twin-engine propeller-driven transport-type airplane with a wing loading of about 25 pounds per square foot.

SYMBOLS

t	time, sec
$\alpha_{f,A},\alpha_{f,B},\alpha_{f,term}$	elevation angles of airplane relative to flare transmitter, deg
$\alpha_g,\alpha_{g,A},\alpha_{g,B},\alpha_{g,C}$	elevation angles of airplane relative to glide-slope transmitter, deg
δ_e	elevator deflection, deg

EQUIPMENT

Guidance

Glide slope.- Glide-slope guidance was provided by a biangular guidance system which consisted of two ground-based transmitters (glide slope and flare), two airborne receivers (one for each transmitter), and an airborne flare-path computer. (See refs. 2 and 3.) Each transmitter sent out coded signals which were received in the airplane and decoded to give the elevation angle of the airplane relative to the particular transmitter. Elevation angles up to 20° could be measured.

The geometry of the guidance system is illustrated in figure 1. The rear (flare) transmitter was located 3000 feet down a 10,000-foot runway at Langley Air Force Base, Virginia, and about 300 feet to the right of the runway center line. The forward (glide-slope) transmitter was located near the approach end of the runway for some of the tests and 1000 feet ahead for other tests giving a distance of 3000 and 4000 feet between sites. As shown in the figure, the forward transmitter provided glide-slope guidance (A to B) and the rear transmitter provided flare-path guidance (B to C) and terminal-angle guidance to touchdown (C to D).

Flare.- Several flare paths were studied during the investigation. These flare paths were generated by the flare-path computer as a function of time. The generation of the flare paths was triggered when the ratio of angles relative to each transmitter reached a predetermined value. During the flare, the airplane was directed along a path (BC, fig. 1) so that the angle relative to the flare transmitter was $\alpha_{f,B}$ at flare trigger and varied with time until it reached a final glide-slope angle $\alpha_{f,term}$. Inasmuch as the directed flare was generated as a function of time only, the flare path in space varied with

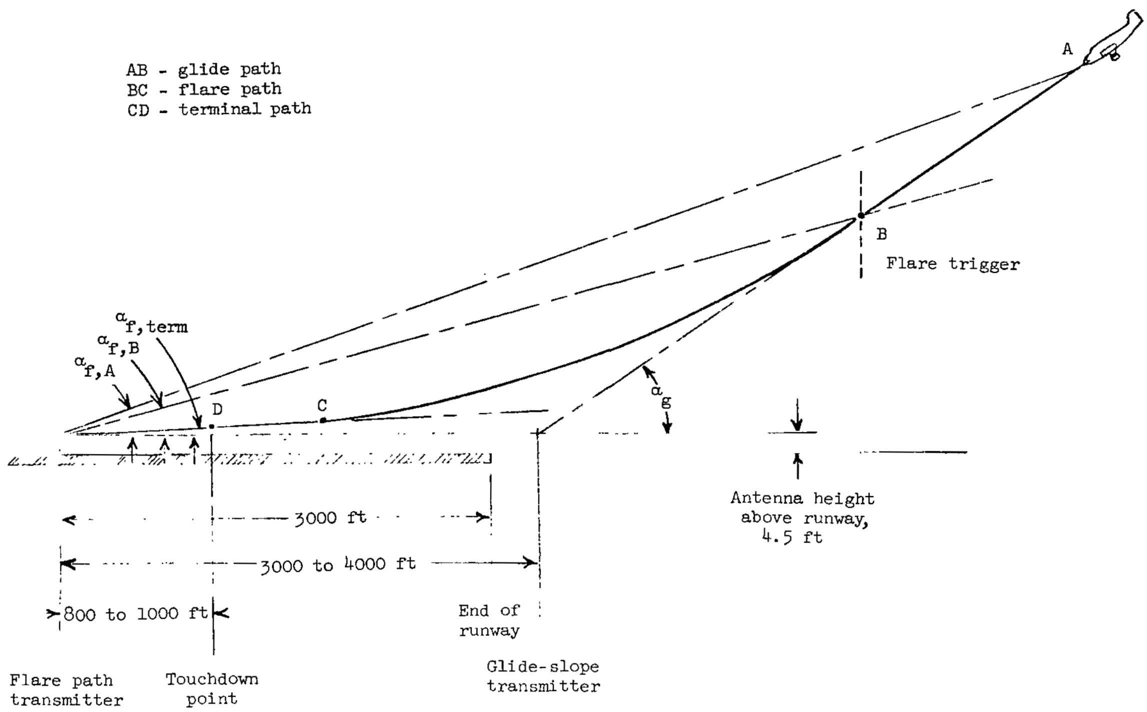

Figure 1.- Biangular guidance system.

airplane ground speed. Therefore, the selection of a time-varying function which would result in a desirable flare path in space required some degree of knowledge of the expected airplane ground speed. Figure 2 shows the variation in space coordinates of a given flare function of 34 seconds duration at three different values of ground speed: 67, 77, and 87 knots. The solid line AB represents a directed path which occurred during the investigation when the average ground speed was about 77 knots. The touchdown point for the 0.4° terminal angle was about 1000 feet ahead of the flare transmitter. A ground speed of 87 knots would be the highest acceptable speed for this flare function because this path AD terminates at the touchdown point and a greater speed would stretch the path beyond the desired touchdown point. Aside from considerations of acceptable speed margins above stall, the lower speed limit would be set to keep the airplane ahead of the glide slope, that is, so as not to require the airplane to duck below the original glide slope. The small hump at the start of the flare was not found to be objectionable by the pilots and this hump helped to keep the directed flare path from ducking below the original glide slope when the ground speed was lower than expected. (Note path AC in fig. 2.)

Directional guidance.- The guidance for the horizontal plane was provided by the localizer used in the Instrument Landing System (ILS) at Langley Air Force Base. This localizer provided an angular deviation system with the origin 1500 feet beyond the runway on the extended center line (11,500 feet from the approach end of the runway).

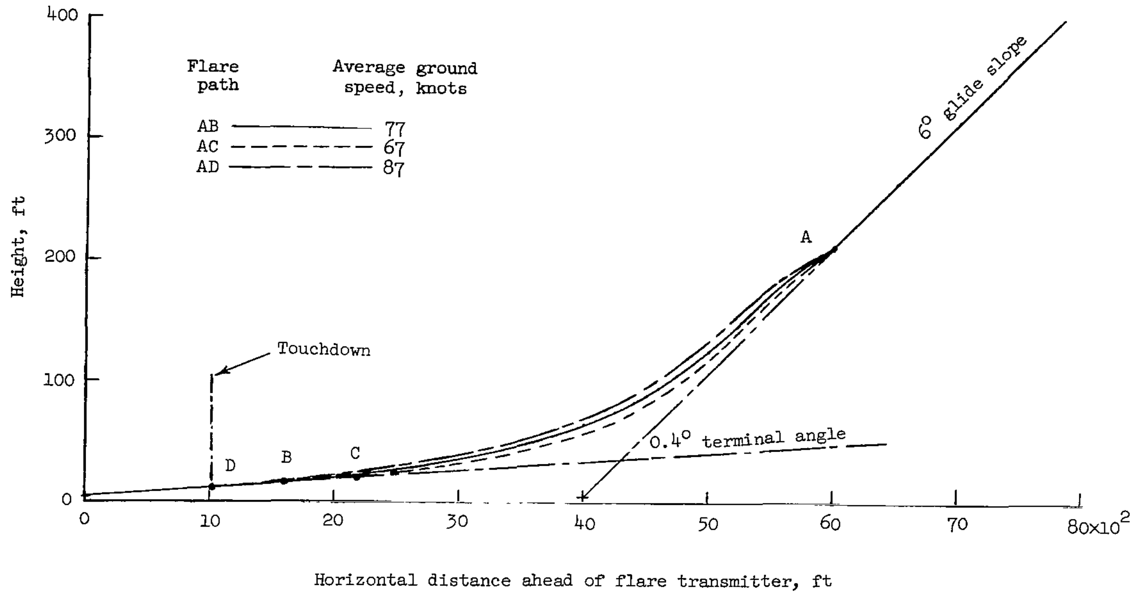

Figure 2.- Flare paths of 34 seconds duration for three ground speeds.

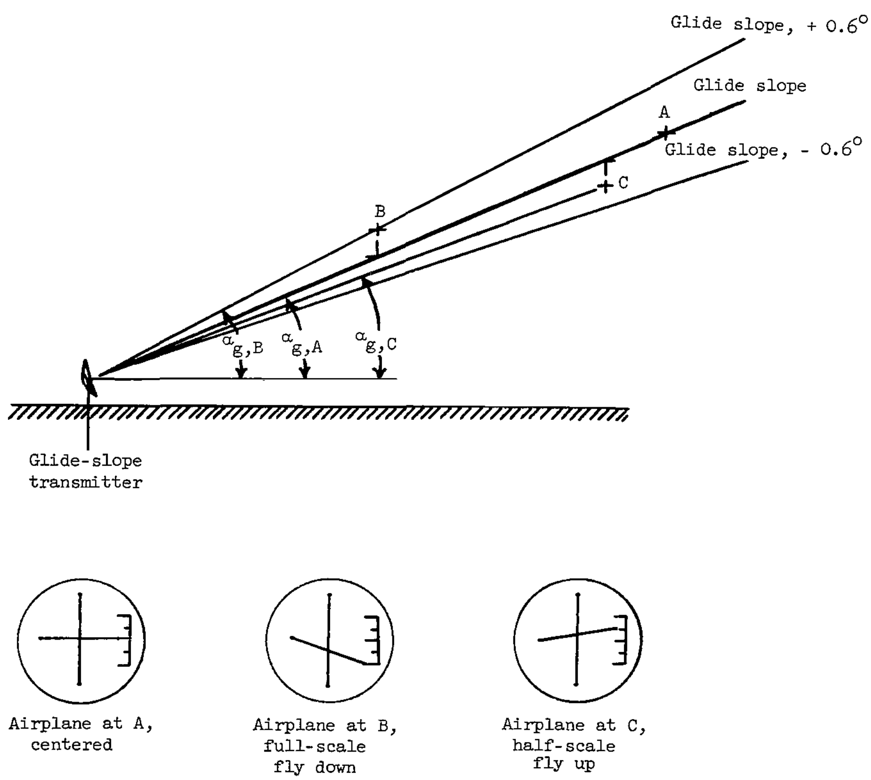

Figure 3.- Glide slope and cross-pointer indications for several positions relative to glide slope.

Guidance display.- Deviations from the desired flight path were displayed to the pilot on a cross-pointer indicator which presented the flight-path deviations in angular units as is standard in present-day ILS. Full-scale deflection of the glide-slope needle represented a deviation of $\pm 0.6^{\circ}$ from the flight path as measured at the forward transmitter for the glide slope and at the rear transmitter for the flare. A given indicator deflection, therefore, represents an increasing sensitivity or a decreasing distance from the desired path as the transmitter is approached. This sensitivity change is illustrated in figure 3 which shows that the linear displacement for half-scale deflection at point C is the same as that for full-scale deflection at point B. After flare trigger, the flight-path deviation is measured relative to the rear transmitter rather than the front transmitter. From figure 4(a) it can be seen that this will result in an abrupt decrease of sensitivity of the glide-slope needle of the cross-pointer indicator.

Full-scale deflection of the localizer needle represented a deviation of $\pm 2.5^{\circ}$ from the desired directional path as measured from a point 11,500 feet from the approach end of the runway. The displacement represented by full-scale deflection of the localizer needle is shown in figure 4(b).

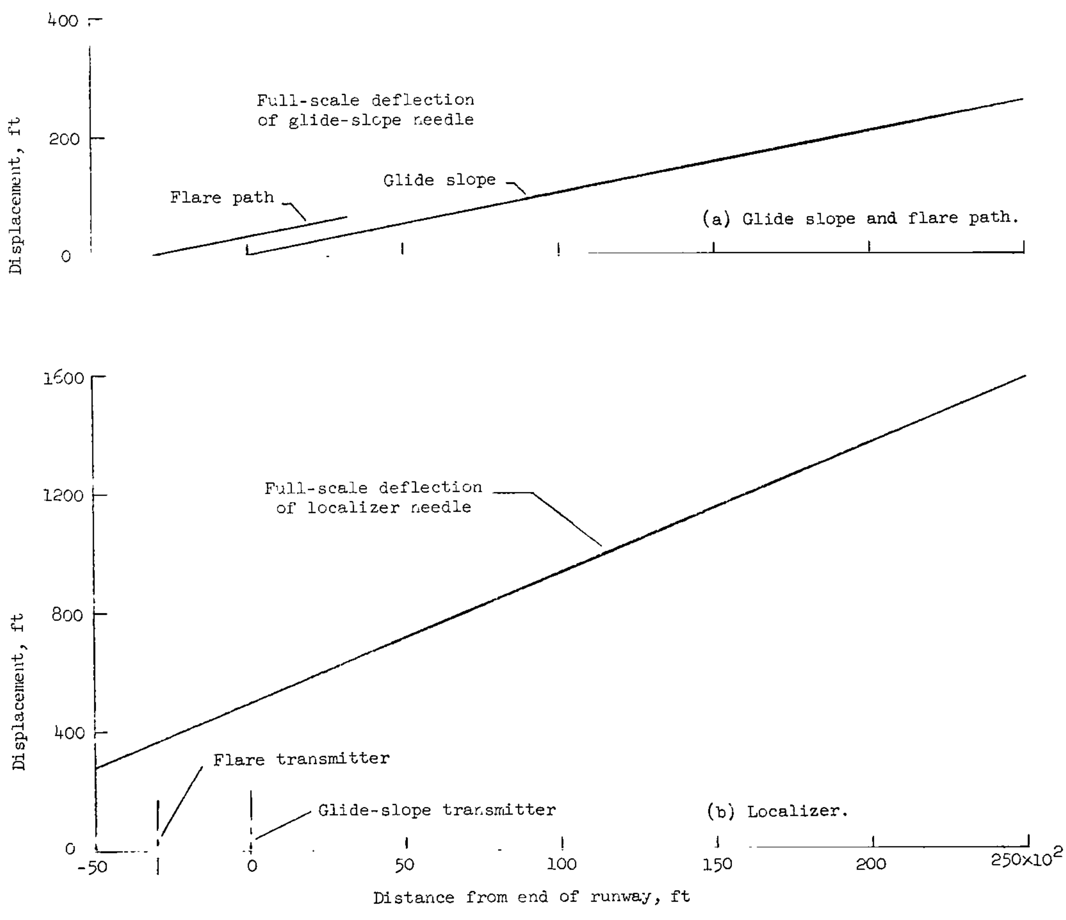

Figure 4.- Variation of displacement represented by full-scale ILS cross-pointer deflection with distance from end of runway.

Airplane and Instrumentation

A C-47 airplane was used for this investigation, and a description of this airplane may be found in reference 4. The approaches were made with the gear down and half-flaps for the $2\frac{1}{2}^{\circ}$ glide slopes and full-flaps were used for the 6°, 7°, 8°, 9°, and 10° glide slopes. The airplane had a wing loading of about 25 pounds per square foot.

The airplane was instrumented with standard NASA flight test instrumentation to measure and record the following quantities: airspeed, pressure-altitude, vertical acceleration at the center of gravity, flap position, elevator position, deviation of glide-slope needle, deviation of localizer needle, angle measured by glide-slope receiver, and angle measured by flare receiver. All recording instruments were correlated by an NASA timer. Additional cockpit instrumentation included two angle indicators to display the glide-slope and flare angles and a panel light to indicate the flare trigger.

Simulator

A fixed-base simulator (fig. 5) was also used in this investigation. Linearized six-degree-of-freedom equations of motion, axis transformation, and

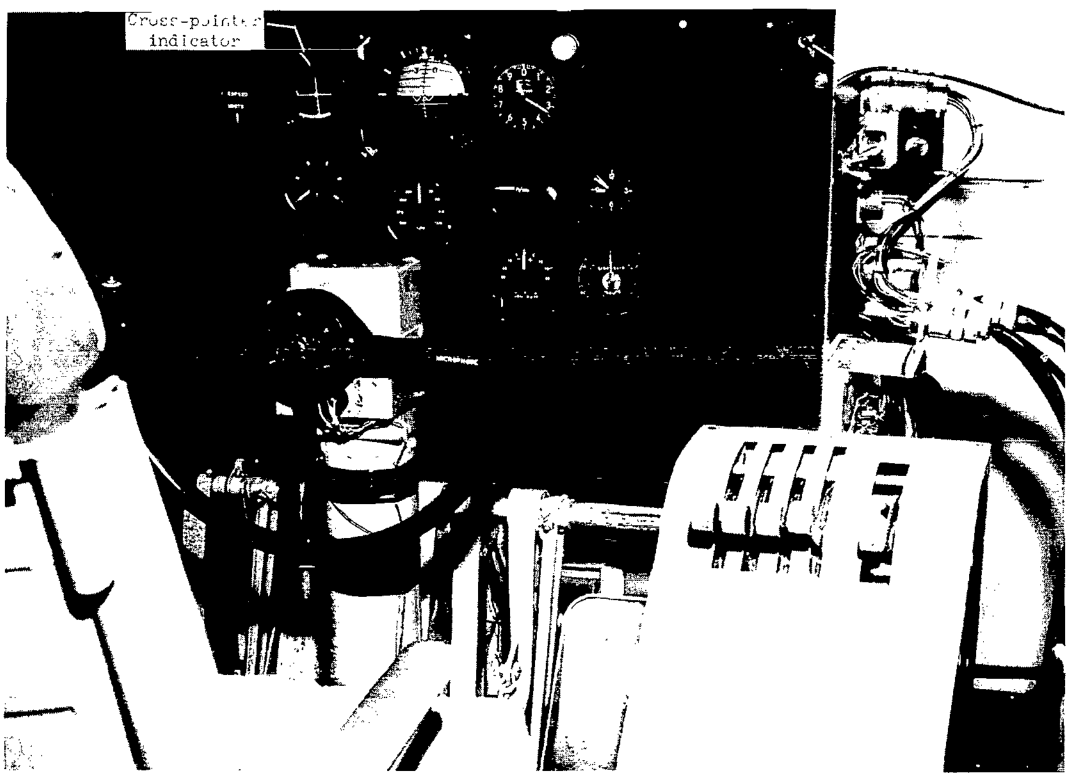

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Figure 5.- Fixed-base cockpit simulator.

equations representing the biangular guidance and localizer systems were programed on an electronic analog computer. Aerodynamic coefficients representative of a C-47 airplane in the landing approach configuration were used with the equations of motion. The cockpit instruments were airspeed, altitude, rate-of-climb, pitch-roll attitude, heading, cross-pointer, and percent of full thrust indicators, and a light to indicate the flare trigger. The control movement was adjusted to represent that of the C-47 airplane and the linear spring forces were representative of the C-47 control forces.

TESTS

Pilots

The pilots participating in this program were NASA experimental test pilots with varying degrees of experience ranging from over 20 years to a few years of flight test work. While these pilots have not had the opportunity to make ILS approaches as often as airline pilots of comparable years of experience, their background does make them capable of providing expert opinion to assess the relative difficulty of flying various glide slopes and flare paths.

Instrument Flight Simulation

In order to simulate instrument flight, the pilot wore a headpiece (fig. 6) which cut off his exterior vision while allowing an unobstructed view of the instrument panel. The copilot acted as a safety pilot by taking over the controls whenever necessary to prevent the occurrence of an unsafe condition.

Throttle Control

During some of the approaches, the copilot operated the throttle to maintain the desired airspeed in order to simulate an automatic throttle control.

Test Procedure

The instrument landing approaches were flown as shown in figure 7 with the airplane approaching the outer marker in level flight at an altitude which would allow the pilot to push over and acquire the glide slope near

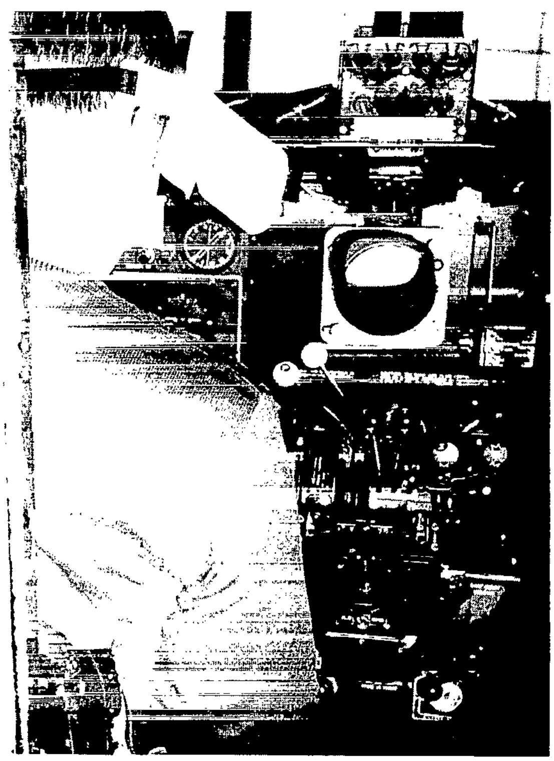

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Figure 6.- Headpiece worn by pilot to simulate instrument flight.

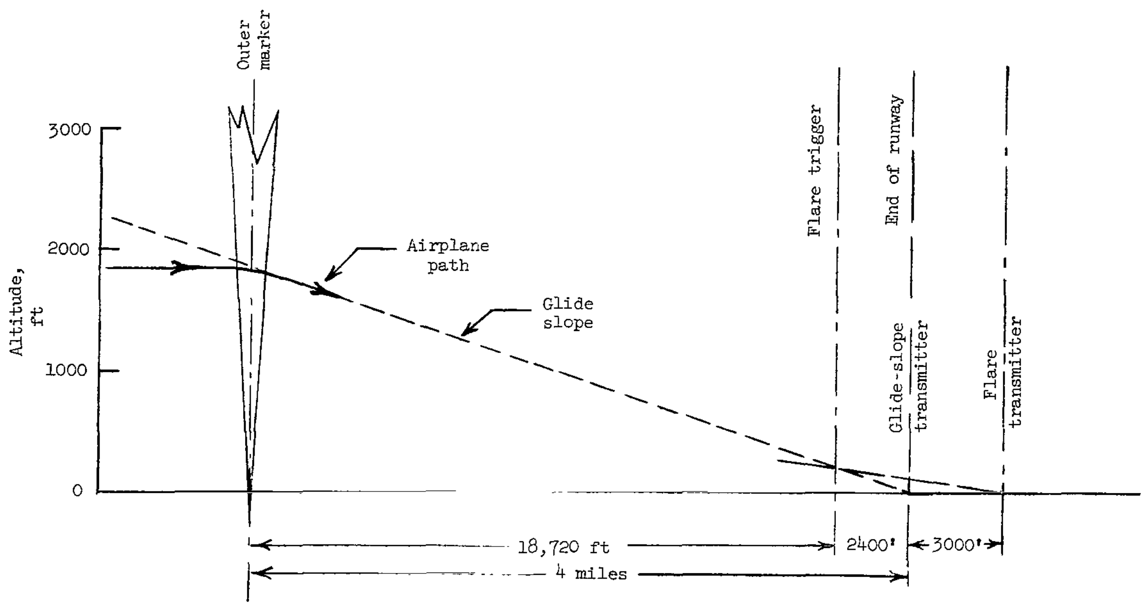

Figure 7.- Airplane path used to acquire glide slope.

the outer marker. The pilot then attempted to fly an instrument approach by using the ILS cross-pointer indicator and the heading indicator for guidance. After several successful instrument approaches were made at a given glide slope, the angle was increased until an upper limit was reached which, in this case, was only flown visually under ideal wind conditions. Pilot opinion supported by measured flight-path deviations was used to establish the maximum glide slope that would be feasible for operational use under varying wind conditions that would be encountered in day-to-day use.

Several pilots were used to compare the approaches made at this maximum operational glide slope with approaches made at the conventional $2\frac{1}{2}^\circ$ slope. Flare-path guidance was provided during these tests and the pilot's task was to continue the instrument approach to touchdown, if possible.

Simulator Tests

The simulator tests were made only for one glide slope (6°) and were used primarily to investigate flare-path geometry. These tests were made in the same manner as the flight tests; that is, the airplane intercepted the glide slope from level flight at a distance of about 4 miles from the end of the runway.

RESULTS AND DISCUSSION

Glide Slope

Definition of maximum operational glide slope.- The main purpose of this investigation was to determine the maximum glide slope feasible for day-to-day operational use. The maximum feasible glide slope would be one which could be flown without too much deviation from the desired glide slope and would not cause enough increase in pilot workload to make the procedure unreliable. The power required for the steady speed down the glide slope should be such that there is sufficient margin to steepen the flight path by further reduction of power if the airplane gets above the glide slope because of some disturbance such as gusts.

Glide-slope deviations.- The angular deviations above or below the glide slope are given in figure 8 as time variations for several tests of each glide

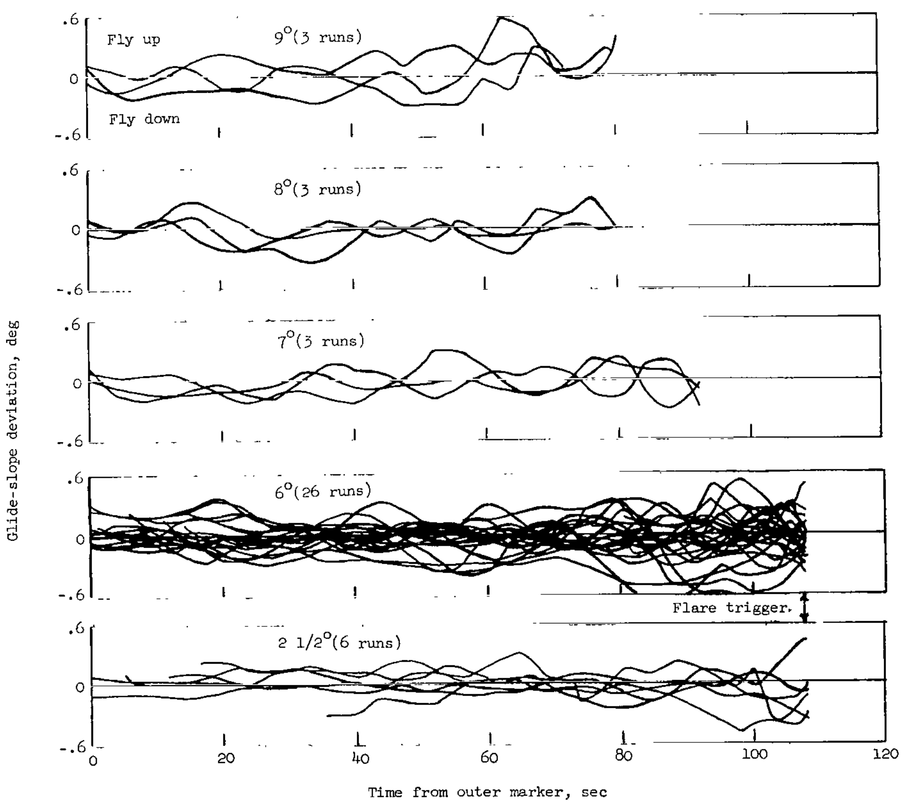

Figure 8.- Variation of glide-slope deviation with time starting at outer marker for $2\frac{1}{2}^{\circ}$, 6°, 7°, 8°, and 9° glide slope.

slope investigated. The time scales are related approximately to a common point (outer marker) which is about 4 miles from the end of the runway. Since the airspeeds varied within the range of 70 to 100 knots and generally were about 85 knots, the time variations for each glide slope, in general, represent a corresponding variation with distance along the same portions of the glide slope starting at the outer marker. The time variations for the $2\frac{1}{2}^{\circ}$ and 6° slopes cover the distance from the outer marker to the point of the initiation of flare, a distance of about $3\frac{1}{2}$ miles (fig. 7). The tests at 7°, 8°, and 9° were terminated by the pilot at altitudes of 200 to 300 feet instead of at the flare trigger point.

The deviations for the $2\frac{1}{2}^{\circ}$ slope are rather small with the exception of a few excursions. (See fig. 8.) For the 6° slope, there are larger excursions but, in general, the majority of the lines are concentrated in a rather small band. As the origin is approached, a gradual increase of glide-slope deviation indicates the effect of increasing needle sensitivity due to the display of glide-slope deviation in the form of angular displacement. The data for the 7° and 8° slopes indicate that the pilot was able to fly these glide slopes with reasonable precision. The data for the 9° slope indicate that the pilot was never really established on this glide slope for any length of time.

The time histories in figure 8 cannot give a clear-cut indication of the relative difficulty in maintaining good control of the glide path for two reasons: pilots have a well-known ability to adapt to a difficult task and produce results comparable to lesser tasks and the number of runs was insufficient to give an average set of results, particularly at the higher angles. Because of these factors, the selection of the maximum operational glide slope was primarily based on pilot opinion. In the opinion of the pilots, the 6° slope was more difficult to fly than the conventional $2\frac{1}{2}^{\circ}$ slope but they felt that, with a reasonable amount of experience, the 6° slope could be used for normal operations. The 7° and 8° slopes were no more difficult to fly in calm air than the 6° slope but the 9° slope was appreciably more difficult. Because of the low power required for the 9° slope, to keep from flying out of the top of the slope was difficult and to get back to the slope after getting above it was extremely difficult. For this same reason - low power required - it was believed that the 7° and 8° slopes would be difficult to fly under gusty conditions; therefore, the 6° glide slope was determined to be the maximum operational glide slope as defined in the preceding section.

Effect of gusts.- Both the $2\frac{1}{2}^{\circ}$ and 6° slopes were flown under gusty conditions and the flight-path control was adequate as indicated by the comparison of flight deviations shown in figure 9 for gusty conditions with the deviations from figure 8 for relatively calm conditions. The wind conditions were recorded at the Langley Research Center from an instrument height of 70 feet at a position about 2000 feet to the left of the approach end of the runway used for these tests. The winds recorded at the time of these runs were headwinds of 10 knots with gusts to 16 knots. While successful approaches were made under

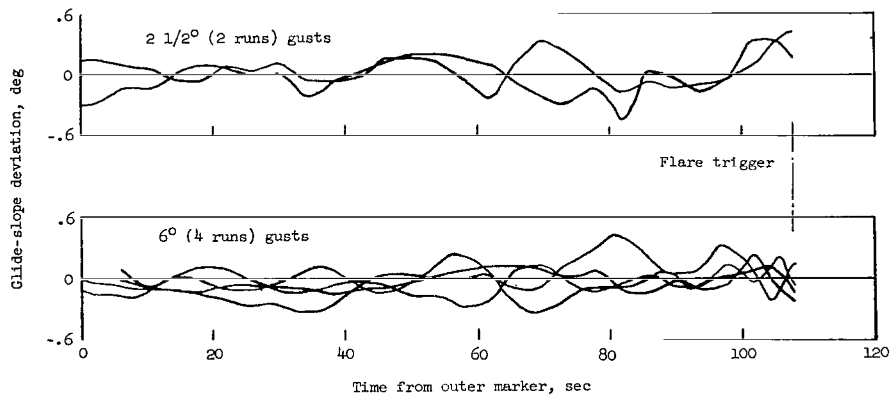

Figure 9.- Maximum glide-slope deviations starting at the outer marker for $2\frac{1}{2}^{\circ}$ and 6° glide slopes in gusty air.

these wind conditions, considerably more pilot effort was required than for calm air. To quote one pilot, "The C-47 requires much 'wrestling' in rough air."

Glide-slope limit.- In order to determine the maximum glide-slope capability of the C-47, one test was made visually along a 10° glide slope. The propellers were windmilling which resulted in additional drag rather than thrust and the air was calm so that the airplane did not get displaced above the glide slope. This 10° glide slope then represents the limit glide angle of this airplane with gear down, full flaps, and no power for airspeeds between 75 and 85 knots.

Directional Control

In order to illustrate the effects of directional control problems on both the lateral and vertical flight path, the time variations of flight-path deviation and elevator deflection are given in figure 10 for a 6° approach and flare to touchdown. The airplane was flown into the glide slope from a position below and to the right. The airplane was pushed over and the glide-slope needle was approximately centered at $t = 20$ seconds. The airplane proceeded down the glide slope with both needles well centered for about 40 seconds after which the airplane drifted off course to the right (about 1/4 full-scale localizer-needle deflection at $t = 85$ seconds) and then was overcorrected to the left (slightly greater than 1/4 full-scale needle deflection at $t = 120$ seconds). The lateral flight-path error was reduced during the flare and the localizer was centered just prior to touchdown.

The particular point to be noted here is the deterioration of the smooth flight path along the glide slope after the pilot had to concentrate on the lateral problem (after $t = 80$ seconds). In order to make a lateral correction, the pilot had to decide how much bank was needed and when to take it out. Then, as the desired course was approached, this procedure was repeated in the opposite direction in order to come out on course with the proper heading. While concentrating on this procedure, the pilot had less time to concentrate on the

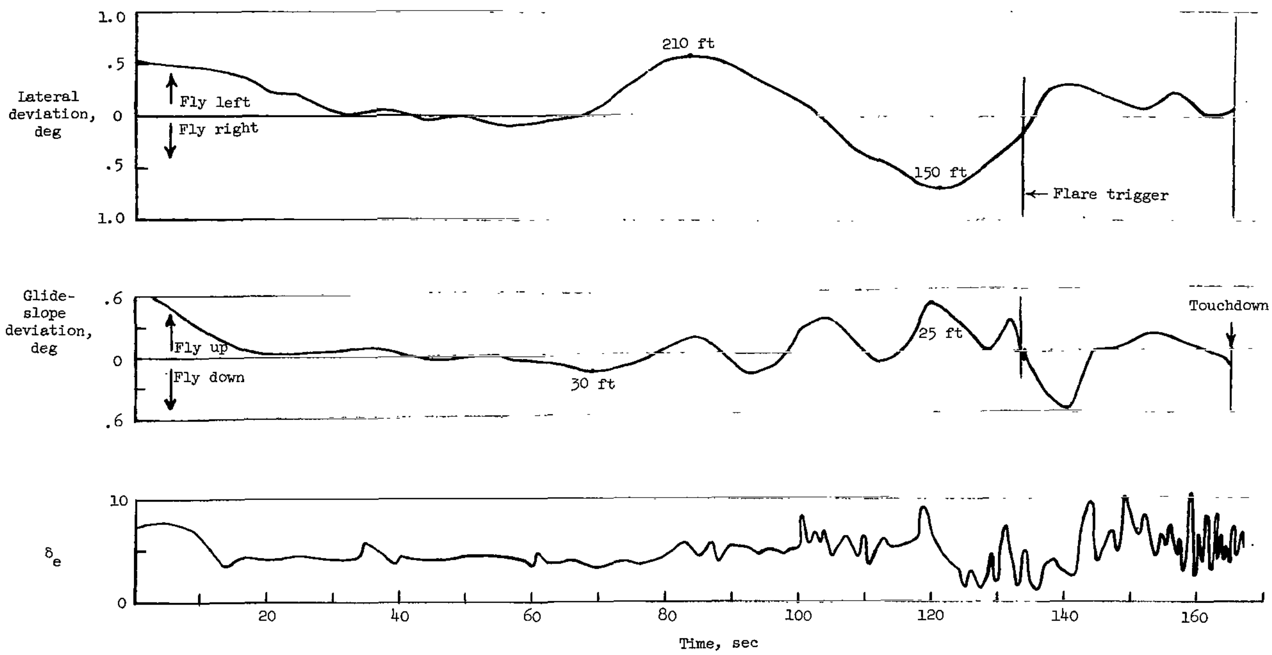

Figure 10.- Time histories of glide-slope and flare-path deviations, localizer deviations, and elevator deflections for a 6° approach and flare to touchdown.

glide slope and it was also difficult to maintain the proper glide slope while maneuvering in this fashion. The increased effort in glide-path control and the effect of increased indicator sensitivity is illustrated by the increased frequency and amplitude of elevator motion near the end of the run.

The following statement made by one of the pilots is representative of the opinion expressed by all of the pilots who participated in this investigation: "Longitudinal control of the flight path is not difficult in itself. Lateral directional control requires much time and effort, detracting from glide control. Control of lateral directional axes with autopilot and manual longitudinal control would seem workable and desirable."

Small directional changes were difficult to apply with precision owing to the rather large breakout forces and to the large wheel movement required to start a bank angle in the C-47. Once the control takes effect, the airplane responds quickly, making it difficult to avoid overshooting when a small change is desired.

Flare Path to Touchdown

An additional objective of this investigation was to determine suitable flare paths for instrument flight under manual control from these steep approach angles. The results of the simulator study and the flight investigation indicated that the flare path should be much longer than that for visual landing.

Based on the results of the simulator study and the flight tests, the best flare paths required about 22 to 34 seconds to change the flight path from the 6° glide slope to a small terminal angle. Flare times longer than this were not investigated since this would have resulted in moving the glide-slope origin too far from the end of the runway. These flare times of 22 to 34 seconds allowed the flight path to be changed at a rate of about 1° every 4 to 6 seconds so that very low "g" forces were felt and the pilot was able to use the glide-slope needle in just about the same manner as it was used down the glide slope (that is, by making small attitude changes as required to keep the needle centered).

In the opinion of the project pilot, the best flare path that was used with the 6° glide slopes is shown in figure 11. The glide-slope transmitter was placed 4000 feet ahead of the flare transmitter and the flare initiation point was 2000 feet ahead of the glide-slope transmitter (Flare height = 210 feet). The terminal portion of this path was a constant angle of 0.4°. This test was made to touchdown with small vertical deviations throughout the glide path and flare path. However, touchdowns with the pilot hooded occurred occasionally rather than frequently. The lateral-directional control problem was felt to be the primary reason for frequently missing the touchdown.

Based on these tests, hooded approaches to touchdown are not feasible with the C-47 under manual control when the pilot has only the standard ILS cross-pointer indicator, heading indicator, and basic flight instruments for guidance information. The minimum ceiling was not determined but it was felt that the minimum approach height would have been limited by the lateral guidance display

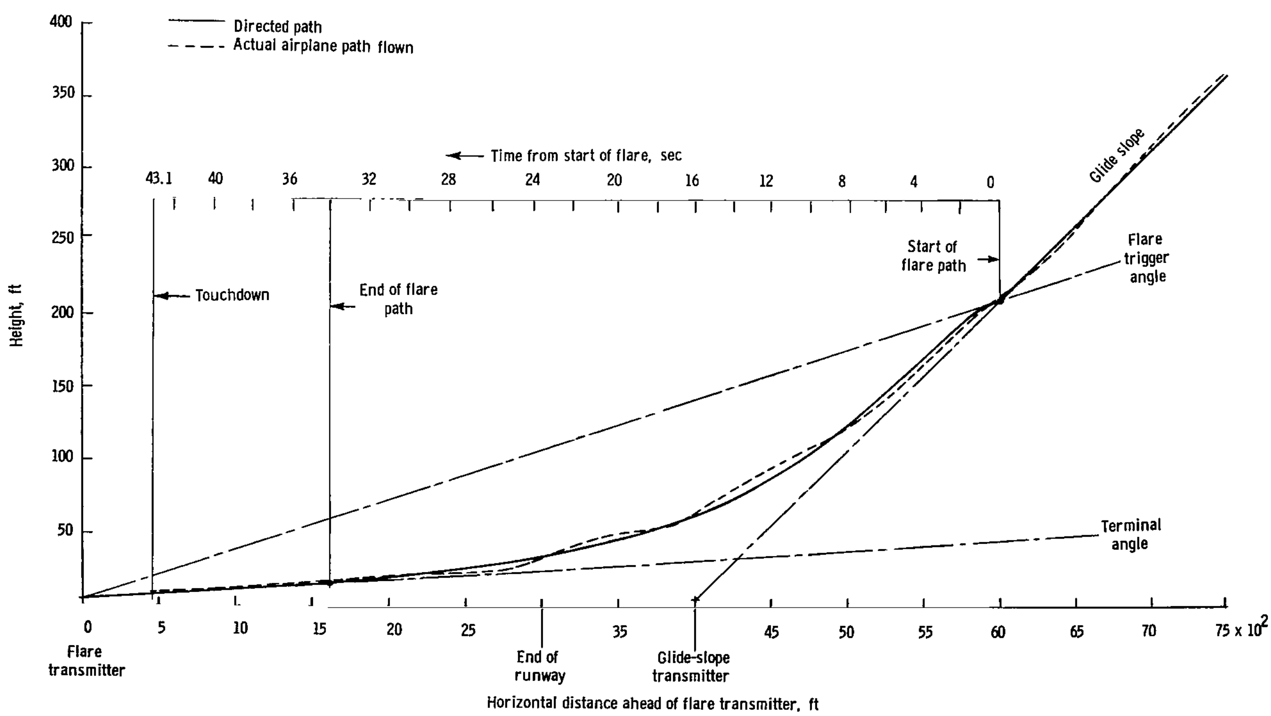

Figure 11.- Flight path for a typical run with a 34-second flare.

and the airplane and pilot capabilities rather than by the vertical flight-path guidance equipment which, in this case, was capable of providing a well-defined glide slope and flare path to touchdown.

It is difficult to compare the flare paths from the $2\frac{1}{2}^{\circ}$ glide slope with the flare paths from the 6° glide slope since the lateral-directional control was equally predominant in each instance and a touchdown could not be made consistently in either case. However, the pilots felt that if the lateral-directional problem could be eliminated, the flight path could be controlled manually in the vertical plane to allow touchdowns consistently from either the 6° slope or the $2\frac{1}{2}^{\circ}$ slope.

Speed Control

Throttle position was not recorded during these tests so that a comparison of airspeed time histories means little in relating the pilot's effort required to maintain a desired speed. The procedure for these tests was generally to maintain the airspeed at about 100 mph (87 knots) on the glide slope and let the speed drop to about 80 mph (70 knots) during the flare. Power had to be added during the flare from the 6° glide slope in order to keep the airspeed from dropping too much. This speed drop was observed during the simulation study in several runs where the power was not changed during the flare and the speed dropped from about 83 knots to 59 knots.

Some runs were made with the safety pilot operating the throttles and the hooded pilot found this simulated automatic speed control to be very effective in decreasing the workload during the flare; however, the lateral-directional control was still too difficult to allow touchdowns to be made consistently. The project pilot felt that with lateral directional control managed by a split-axis autopilot, the longitudinal control could be managed manually without an automatic throttle. One of the other pilots, however, felt that an automatic throttle would be a necessity for use with the 6° glide slope.

CONCLUDING REMARKS

A flight investigation has been conducted to determine the steep instrument approach capabilities and limitations of a C-47 airplane under manual control. This study included an investigation of flare paths suitable for transition from the steep glide slope to a final terminal angle to touchdown.

The maximum glide slope feasible for operational use in an instrument approach was 6°. This limit was established by the lowest value of thrust that could be used and still provide a margin for thrust reduction as needed for flight path and speed control rather than by the pilot's ability to fly steeper angles by using instrument guidance. More pilot effort and concentration were required to fly the 6° glide slope than were required for the conventional

$2\frac{1}{2}^{\circ}$ slope and the flight-path deviations were also somewhat greater for the 6° slope.

All pilots were in agreement that the greatest problem during the instrument approach or flare was the effort required to maintain the proper lateral-directional control. In the opinion of most of the pilots, instrument approaches to touchdown from the 6° slope could be made repeatedly with manual longitudinal control if automatic lateral-directional control were available.

The most suitable flare paths were those which required 4 to 6 seconds per degree of flight-path change from the glide slope to the final terminal angle.

Manual instrument approaches to touchdown from either the 6° slope or the conventional $2\frac{1}{2}^{\circ}$ slope are not feasible with the C-47 under manual control when the pilot has only the standard cross-pointer indicator, heading indicator, and basic flight instruments for guidance information. Touchdowns were made occasionally but not consistently as would be required under bad weather conditions.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 11, 1964.

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